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Determination of Flow Resistance Coefficients Due to Shrubs and Woody Vegetation

by Ronald R. Copeland

PURPOSE: The purpose of this Technical Note is to transmit results of an experimental investigation into the effect of vegetation (particularly ground cover plants, small trees, and shrubs) on flow resistance.

INTRODUCTION: An important consideration for determining the stage-discharge relationship in rivers and streams is the effect or influence of vegetation on the overall head loss along a channel and in the overbank. Plants in the floodplain and along the banks can increase or even decrease the effective flow resistance. The vegetation may be natural or it may have been planted to improve aesthetics or habitat, to prevent erosion, or for other reasons.

Hydraulic losses and drag due to actual plants were measured at the Utah State University Water Research Laboratory utilizing a large wide flume and a smaller sectional flume. Research in the flume resulted in the collection of data from more than 220 experiments with 20 different plant species. Experiments were conducted with both homogeneous and mixed plant groupings. Single-stem and multiple-stem plants were included in the plant types evaluated. Plants with and without leaves were evaluated. Plant density, spacing, and size were varied in the experiments. Plants were evaluated over a range of velocities and depths. A methodology was developed from the laboratory data to predict head loss and resistance coefficients as a function of slope and depth. Input data can be collected from the field or estimated plant characteristics may be used in the methodology.

The evaluation of vegetative impacts on proposed and existing channels to determine flow capacity and water-surface elevations requires proper hydraulic roughness values for shrubs and other aesthetically and environmentally desirable plants. Given the near complete lack of hydraulic roughness values for shrubs and similar vegetation, the accurate estimation of channel capacity and water-surface elevations has previously been difficult at best. Details of the study may be found in Freeman, Rahmeyer, and Copeland (in preparation).

RESISTANCE COEFFICIENTS: Resistance to flow is typically characterized by a roughness coefficient. The most commonly used equation for flow resistance is the Manning's equation. The ratio of shear velocity to mean velocity, V_* / V , is another form of resistance coefficient, and may be thought of as the ratio of shear stress to inertial force. All variables are defined in Appendix I. There are other resistance coefficients in use including the Darcy-Weisbach friction factor, f , and the Chezy C . These can all be converted easily to Manning's n . In this study, resistance equations were developed for the shear velocity to average velocity ratio because it is dimensionless and has a sound theoretical basis, and for the Manning's coefficient, because its use is widespread. The Manning's resistance coefficient for vegetation is calculated in

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conformity with the Cowan (1956) method for additive resistance. This method consists of additions to roughness for various surface irregularities and vegetation.

STIFFNESS MODULUS: The modulus of plant stiffness, E_s , is critical to the calculation of resistance because of the flexibility of the plants and the deformation of leaf masses due to the flow forces. The modulus of plant stiffness is calculated by

$$E_s = \frac{F_{45} H^2}{3 I} = 6.791 \left(\frac{F_{45} H^2}{D_s^4} \right) \quad (1)$$

The data necessary to use Equation 1 is obtained by measuring the force, F_{45} , necessary to bend the plant to an angle of 45 deg. The 45-deg angle is measured from the initial vertical position to the stem or leaf mass at the point where the force is measured—i.e., at $H/2$ as shown in Figure 1.

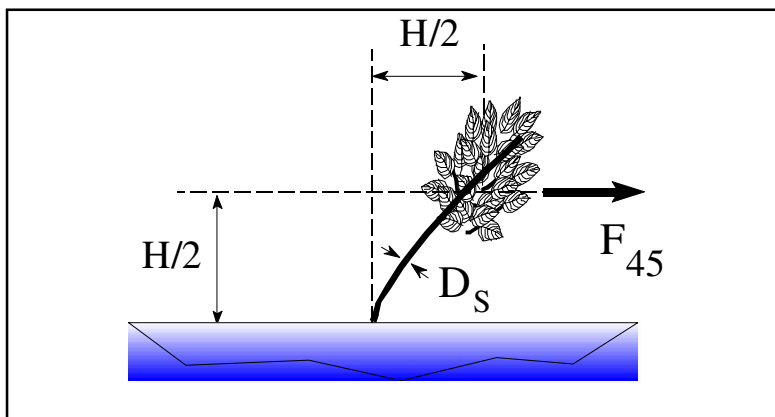


Figure 1. Methodology for measuring plant stiffness for calculating E_s in the field, for plants with effective height of leaf mass approximately equal to the plant height

The research performed in the laboratory and in the field indicated that the stiffness modulus can be estimated from the relationship of E_s to the ratio of H/D_s (Equation 2). This equation gives the modulus in pounds per square foot, while Equation 3 gives the value in newtons per square meter.

$$E_s \left(\frac{\text{lb} \cdot \text{ft}}{\text{ft}^2} \right) = 1.597E05 \left(\frac{H}{D_s} \right) + 454 \left(\frac{H}{D_s} \right)^2 + 37.8 \left(\frac{H}{D_s} \right)^3 \quad (2)$$

$$E_s \left(\frac{\text{N}}{\text{m}^2} \right) = 7.648E06 \left(\frac{H}{D_s} \right) + 2.174E04 \left(\frac{H}{D_s} \right)^2 + 1.809E03 \left(\frac{H}{D_s} \right)^3 \quad (3)$$

Actual field measurements of E_s are recommended where possible. Since the stiffness modulus varies depending on the plant size, it was determined that if the calculated modulus for a particular plant size was divided by $(H/D_s)^{1.5}$, the stiffness modulus became independent of plant size and one value could be used for all plant sizes. Measured stiffness moduli for plants used in the experimental study are reported in Freeman, Rahmeyer, and Copeland (in preparation).

RESISTANCE EQUATIONS FOR SUBMERGED VEGETATION: Results from large flume experiments were analyzed to determine the regression of variables for submerged vegetation. The analysis found that log and polynomial relationships gave a poor data fit while a power relationship had very good results. The parameters in the equations were modified to allow a direct solution for resistance (for a given depth) by combining the original parameters with Manning's equation and the equation for shear velocity. This modification and combination of equations resulted in Equation 4 for shear velocity and Equation 5 for Manning's n . In these equations the resistance coefficients represent the combined resistance of the bed and the plants. Resistance coefficients due only to vegetation must be determined by subtracting the bed resistance. In these experiments the Manning's bed resistance coefficient was found to be 0.02 and V_*/V for the bed was found to be 0.069.

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 0.183 \left(\frac{E_s A_s}{\rho A_i V_*^2} \right)^{0.183} \left(\frac{H}{Y_o} \right)^{0.243} (MA_i)^{0.273} \left(\frac{v}{V_* R_h} \right)^{0.115} \quad (4)$$

$$n = K_n 0.183 \left(\frac{E_s A_s}{\rho A_i V_*^2} \right)^{0.183} \left(\frac{H}{Y_o} \right)^{0.243} (MA_i)^{0.273} \left(\frac{v}{V_* R_h} \right)^{0.115} \left(\frac{1}{V_*} \right) (R_h)^{2/3} (S)^{1/2} \quad (5)$$

It is important to note that the plant characteristics H , A_i , and A_s are the initial characteristics of the plants without the effects of flow distortion. During the experiments, it was observed that since the plants bent with flow, submergence occurred at flow depths less than 80 percent of the plant height. Equations 4 and 5 are to be applied only for submerged flow defined by $Y_o > 0.8 H$.

RESISTANCE EQUATION FOR PARTIALLY SUBMERGED VEGETATION: Data for partially submerged vegetation were analyzed to determine the regression of variables. The regression analysis again found that a log relationship gave a poor fit of data while a power relationship produced very good results. Equations 6 and 7 fit the data well and allow direct solution for resistance if the flow depth is known. Here again, in these equations the resistance coefficients represent the combined resistance of the bed and the plants. Resistance coefficients due only to vegetation must be determined by subtracting the bed resistance. In these experiments the Manning's bed resistance coefficient was found to be 0.02 and V_*/V for the bed was found to be 0.069.

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 3.487E-05 \left(\frac{E_s A_s}{\rho A_i^* V_*^2} \right)^{0.150} (MA_i^*)^{0.166} \left(\frac{V_* R_h}{v} \right)^{0.622} \quad (6)$$

$$n = K_n 3.487 E - 05 \left(\frac{E_s A_s}{\rho A_i^* V_*^2} \right)^{0.150} \left(M A_i^* \right)^{0.166} \left(\frac{V_* R_h}{\nu} \right)^{0.622} \left(\frac{R_h^{2/3} S^{1/2}}{V_*} \right) \quad (7)$$

The blockage area in Equations 6 and 7 was changed to an effective area, A_i^* , since only a portion of the leaf mass produces blockage under partially submerged flow conditions.

CONCLUSIONS: When plants were submerged, it was observed that the plant leaf mass tended to trail downstream forming a streamlined, almost teardrop-shaped profile. The leaf mass shape changed with velocity and became more streamlined with increasing velocity. The effect of this phenomenon was a significant decrease in the drag coefficient and resistance coefficient with velocity. On the other hand, resistance increased with depth for partially submerged plants as the blockage area increased with depth until the plants were submerged. The transition between submerged and partially submerged flow occurred at a depth of about 80 percent of the undeflected plant height.

It was also observed that the leaf mass or foliage canopy diverted flow beneath the canopy. The bottom flow resulted in significant velocities along the channel bed causing general scour and increased sediment transport. The bed velocities were sufficient to transport and move the largest sizes of gravel found in the flume bed.

The hydraulic roughness of a vegetated channel was shown to be a function of the stiffness of the plants growing in the channel, the depth, velocity, and hydraulic radius of the channel, plant density, and frontal area of the plant obstructing the flow. It was determined that the roughness can be calculated directly if the depth of flow is known.

The modulus of plant stiffness, E_s , is critical to the calculation of resistance because of the flexibility of the plants and the deformation of leaf masses due to the flow forces. The research performed in the laboratory and in the field indicated that the stiffness modulus can be estimated from the relationship of E_s to the ratio of H/D_s . Actual field measurements of E_s are recommended where possible. The stiffness modulus can also be estimated from measured values of similar plants. Since the stiffness modulus varies depending on the plant size, it was determined that if the calculated modulus for a particular plant size was divided by $(H/D_s)^{1.5}$, the stiffness modulus became independent of plant size and one value could be used for all plant sizes.

ADDITIONAL INFORMATION: For additional information contact Dr. Ronald R. Copeland, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180, at 601-634-2623 or e-mail Ronald.R.Copeland@erdc.usace.army.mil.

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Appendix I: List of Variables

Numerous variables are used throughout Freeman, Rahmeyer, and Copeland (in preparation). Those variables and their definitions are presented here. Figures I1 and I2 show the measurements that define the variables involving the leaf mass and plant dimensions for submerged and emergent (unsubmerged or partially submerged) flow conditions.

A	Cross sectional flow area, ft^2 or m^2
A_i	Frontal area of an individual plant blocking flow, approximated by the equivalent rectangular area of blockage H' by W_e , ft^2 or m^2
A_i^*	Net submerged frontal area of a partially submerged plant, ft^2 or m^2
A_s	Total cross-sectional area of all of the stem(s) of an individual plant, measured at $H/4$, ft^2 or m^2
b	Width of channel flume, ft or m
C	Chezy resistance coefficient, $\text{ft}^{1/2}/\text{s}$ or $\text{m}^{1/2}/\text{s}$
C_D	Drag coefficient of vegetation, dimensionless
D_s	Stem diameter, measured at a height of $H/4$, ft or m
E	Exponential scientific notation
E_s	Modulus of plant stiffness, lbf/ft^2 or N/m^2
f	Darcy-Weisbach friction factor, dimensionless
f_b	Friction factor for the bed and plants, dimensionless
f_w	Friction factor for the walls, dimensionless
F_{45}	The horizontal force necessary to bend a plant stem 45 deg, lbf or N
F_D	Drag force, lbf or N
F_r	Froude number, dimensionless
g	Acceleration due to gravity = $32.17 \text{ ft}/\text{s}^2$ or $9.806 \text{ m}/\text{s}^2$
H	Average undeflected plant height, ft or m
H'	Undeflected height of the leaf mass of a plant, ft or m
H^*	Undeflected height of leaf mass that is below water surface for a partially submerged plant, ft or m (See Figure I2)
I	Second moment of inertia of cross section of plant stem, ft^4 or m^4
K_n	Units conversion factor for Manning's equation, $1.4861 \text{ ft}^{1/3}/\text{sec}$ or $1.0 \text{ m}^{1/3}/\text{sec}$
L	Channel reach length, ft or m
M	Relative plant density, number of plants per ft^2 or m^2
n	Total Manning's roughness coefficient, including sidewall roughness

n_b	Manning's resistance coefficient for vegetation and channel bed
n_{veg}	Manning's resistance coefficient for vegetation
n_o	Manning's resistance coefficient for the bed
P	Wetted perimeter, ft or m
R_e	Reynolds number, $R_e = V R_h / \nu$
R_h	Hydraulic radius, $R_h = \text{flow area} / \text{wetted perimeter}$, ft or m
R_b	Hydraulic radius for the bed and plants, ft or m
R_w	Hydraulic radius for the walls, ft or m
S	Bed or energy slope, dimensionless
S_o	Bed slope, dimensionless
S_f	Energy slope, dimensionless
V	Mean channel velocity, ft/s or m/s
V_p	Local plant approach velocity in front of the leaf mass, ft/s or m/s
V_*	Shear velocity, $V_* = (g R_h S)^{1/2}$, ft/s or m/s
V_*/V	Resistance coefficient, dimensionless
Y_o	Flow depth, ft or m
W_e	Equivalent average plant width, $W_e = A_i / H'$, ft or m
dy/dx	Unit change in slope of the water surface
γ	Specific weight of water, lbf/ft ³ or N/m ³
ν	Fluid dynamic viscosity, ft ² /s or m ² /s
ρ	Fluid density, slugs/ft ³ (lbf-sec ² /ft ⁴) or kg/m ³
τ_o	Shear stress on channel bottom, $(\tau_o = \gamma R_h S)$, lbf/ft ² or N/m ²

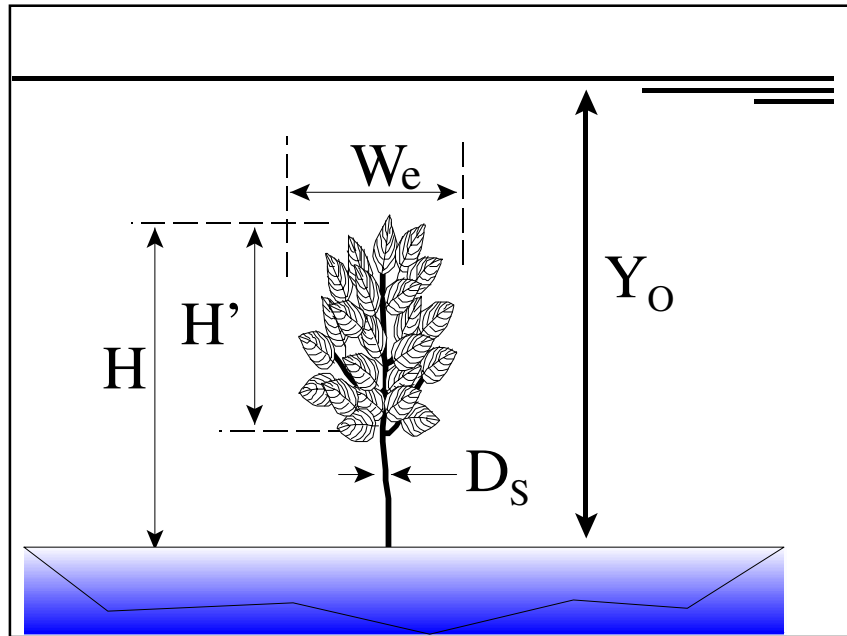


Figure I1. Plant dimension definitions for submerged plants

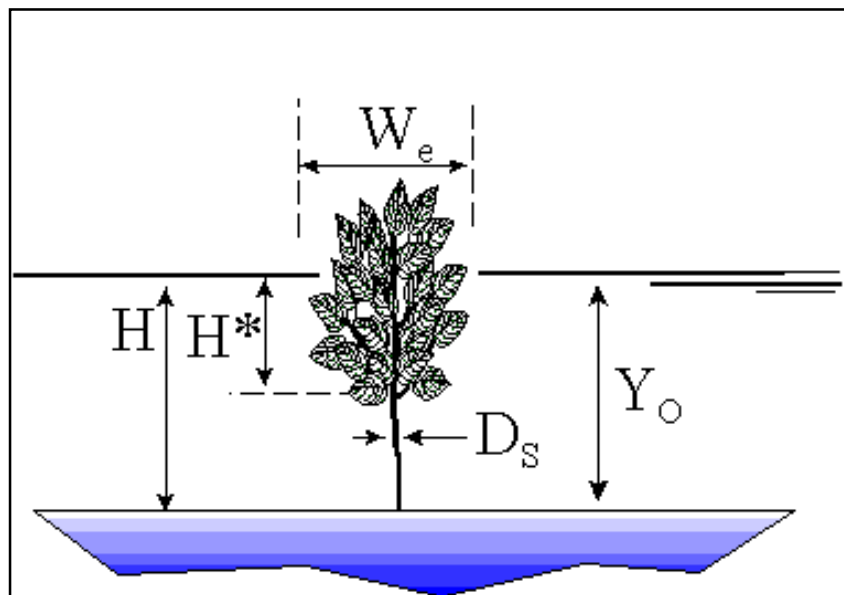


Figure I2. Plant dimension definitions for partially submerged plants